Small Area Y-Ba-Cu-O Thin Films for Applications in Hot-electron Bolometers

Leila R. Vale and R. H. Ono

Abstract **We are investigating the use of very thin, small area $YBa_2Cu_3O_{7-x}$ (YBCO) films on Si substrates for application in hot-electron bolometers. Hot-electron bolometers produced from high-T_C materials will be favored over their low-temperature counterparts in applications of radio astronomy and atmospheric physics where the higher operating temperatures provide distinct advantages. Devices on Si can help advance this technology for bolometric space applications, where a substrate is needed with good thermal conductance and excellent IR performance. Based on our experience with YBCO bolometers and YBCO film growth on Si, we have begun a study of sub-micrometer scale devices. Our typical YBCO films grown on Si by pulsed laser deposition have critical temperatures of 86 K and critical currents of 1-3 x10^6 A/cm^2 at 77 K for YBCO microbridges 45 nm thick. We have made 1-2 µm wide microbridges from YBCO films of 25 nm to 45 nm thick. These microbridges show reduced critical temperatures of 71 K to 81 K, respectively, related to the processing sequence that produces the microbridges.**

Index Terms **hot-electron bolometer, Si substrates, thin film growth, Y-Ba-Cu-O.**

I. Introduction

SUPERCONDUCTING hot-electron bolometers (HEB) have been shown to be high-quality mixers for radiation up to and above 1 THz. Low-noise mixers are desirable as heterodyne receivers for atmospheric and space science. In the latter case, local oscillator (LO) power consumption is particularly restricted. Schottky-diode mixers and superconductor-insulator-superconductor (SIS) mixers are typically used for heterodyne mixing applications, but both have performance limitations. Nb SIS mixers have an upper frequency limit of approximately 1.4 THz and Schottky mixers have LO power demands that limit their usefulness. Nb HEBs have been demonstrated with excellent noise temperature performance, and a recent study shows that Al-based low temperature superconducting (LTS) HEB mixers will provide reduced mixer noise and LO power requirements with adequate intermediate frequency (IF) bandwidth [1]. The need for minimized LO power, good IF matching and bandwidth, and operating frequencies above 1 THz combined with the desire for higher operating temperatures, led to an interest in developing high-temperature superconducting (HTS) HEBs. It has been shown theoretically that $YBa_2Cu_3O_{7-x}$ (YBCO) HEBs can provide good performance characteristics by taking advantage of the phonon cooling of the hot electrons into the normal metal leads [2]. These characteristics are achievable at temperatures easily attainable with inexpensive, reliable, closed-cycle refrigeration that is of special interest in space applications. The use of YBCO HEB necessitates small devices and thin films to achieve the improved performance and increased frequency range. YBCO bridges 1 µm x 1 µm have been fabricated with a thickness of 20 nm and T_C of 80 K and $J_C > 10^6$ A/cm^2 on $YAlO_3$ substrates [3]. With recent processing improvements the same group has reduced the size of the YBCO HEB to a minimum of 0.1 µm x 1.0 µm with comparable T_C and J_C to those previously reported [4].

We report here on work to develop YBCO hot-electron bolometers on Si substrates. A variety of substrates that provide good thermal conductivity can be used to produce epitaxial YBCO for HEB applications. Our choice of substrate reflects our considerable experience in YBCO on Si processing [5] and our interest in utilizing the mature Si technology that allows interchangeability with existing LTS HEB device technology. Figure 1 shows the cross section of a typical HEB with a very thin YBCO superconducting layer and normal metal leads. Also shown are the necessary buffer layers required for YBCO growth on Si substrates. The length, width, and film thickness of the device determine the operating characteristics of a superconducting HEB. By decreasing the length of the device, the IF bandwidth is increased and the LO power required decreases. Decreasing the width and the film thickness of the HEB increases the device resistance, improving the match to both antenna and

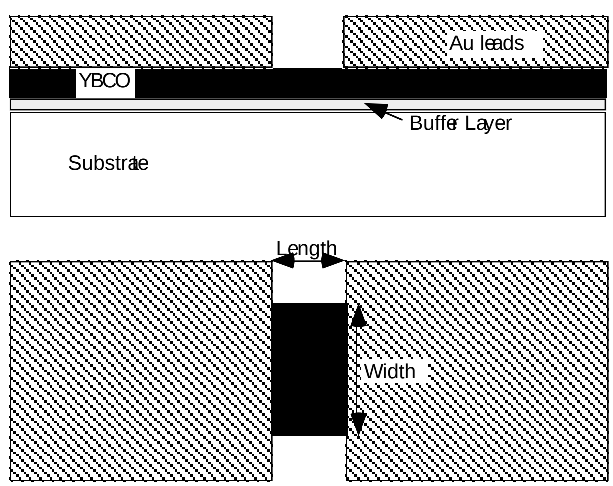

Fig 1.Cross-section and schematic of a YBCO microbridge on Si.

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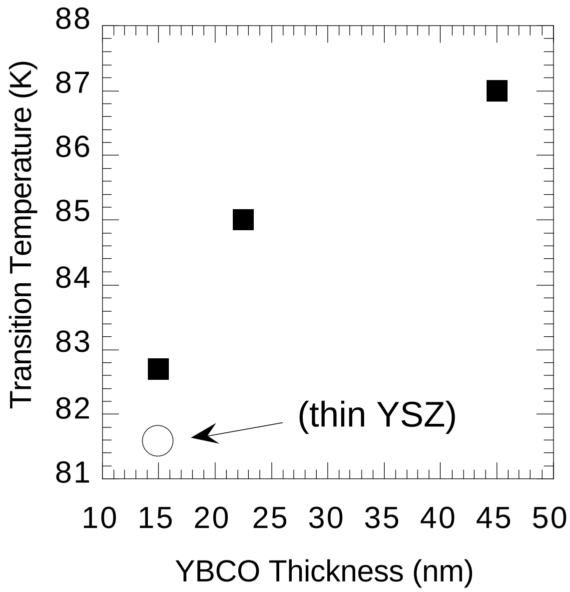

Fig. 2. Plot of critical temperature transitions of three YBCO films of thickness 45 nm, 23 nm, and 15 nm deposited over 170 nm thick YSZ. The circle data point represents a YBCO film of 15 nm thickness deposited on 90 nm YSZ.

IF path. LO powers less than 1 μW can be achieved by reducing the dimensions of the HEB devices to <<1.0 μm^2 with YBCO thickness of order 10 nm [2]. This degree of size reduction will require the use of electron-beam lithography and will be the topic of future work. Here we concentrate on the processing necessary to minimize the device area and film thickness without damaging the YBCO film on Si. We report on the effect on the film T_c and J_c from varying the YBCO and yttria-stabilized zirconia (YSZ) buffer film layer thickness. We also present the electrical characteristics of HEB prototype devices on Si reduced in size to 1.5 μm width and film thickness of 25 nm minimum.

II. FABRICATION

A. Film Growth

The requirements for YBCO HEB devices on Si necessitate that we alter our established film growth technique for 50 nm thick films that have critical temperature T_C~86 K and critical current density J_C~$3x10^6$ A/cm^2 at 77K. Our goal is to routinely produce YBCO films of order 10 nm to 20 nm thickness. The film growth process produces a tri-layer of YBCO, CeO_2, and YSZ. As we studied the effects of YBCO film thickness we also altered the thickness of the YSZ buffer layer. Ultimately, we will study how changes in the buffer layer thickness affect phonon cooling to the substrate. The films were all grown by pulsed excimer laser deposition at temperatures of 770-800 ¡C, in a controlled O_2 pressure of 53-93 Pa (400 mTorr-700 mTorr). The YSZ film thickness was typically 170 nm and the CeO_2 was 20 nm thick. The YBCO thickness was varied from 45 nm to as little as 15 nm. After cooling to room temperature, a film of Au was deposited *insitu* by DC sputtering to a thickness of 25 nm. These unpatterned films have critical temperatures ranging from 87 K (for 45 nm thick YBCO) to 82 K (for 15 nm thick YBCO). Critical temperature transition widths of 1.5 K to 3 K are typical.

Fig. 2 shows the decrease in critical temperature with decreasing YBCO thickness. For YBCO thickness of 45 nm, 25 nm and 15 nm, with YSZ buffer layers of 170 nm, we see T_c values of 87 K, 85 K and 83 K respectively. Currently, the limiting YBCO thickness on Si seems to be 15 nm, since thinner depositions resulted in films with extremely high resistivities that are difficult to contact using 4-point probing. A 15 nm thick YBCO film grown on a thinner YSZ buffer layer (90 nm) showed a further decrease in T_c (81.5 K). Further study will determine the effects of thinner YSZ layers on the thermal boundary resistance of the phonons to the substrate. The decreased critical temperatures are acceptable for an HEB device that requires film thickness of 15 nm or less, to provide improved impedance matching with its antenna and IF circuit.

B. Device Fabrication

The YBCO films of thickness 25 nm and 45 nm were selected for further patterning into HEB prototype devices. Using conventional photoresist-based lithography and ion milling, the films were patterned using a 3-step process that allows electrical measurements of the critical temperature and critical current density at each processing step. The ion-milling parameters were normal incidence, 300 V, 0.5 mA/cm^2, for a rate of 10 nm/min. The processing stages were as follows: (1) 14 microbridges of varying widths, fully coated in Au, were fabricated and underwent initial testing; (2) the microbridges were repatterned and ion milled again to produce prototype HEB devices with width of 1.5 μm; (3) the thin Au film was removed from the bolometer device region of selected devices by yet another patterning step and a reduced energy ion-milling process (80 V) to minimize damage to the underlying YBCO film. The resulting exposed region of YBCO film was of size 1.5 μm width and ~ 4 μm length.

III. ELECTRICAL CHARACTERIZATION

Prior to any patterning, the measured T_c of these films was typically 83 K for 25 nm films and 87 K for 45 nm films. The films underwent the first patterning to produce 14 microbridges, are re-measured, and a baseline T_c was established from a 10 μm wide test strip on each chip. Baseline T_c was 84 K (45 nm thick) and 77 K (25 nm thick) for the 10 μm strip, which is a decrease of several K in T_c from the unpatterned films, for both 25 nm and 45 nm thick test strips. The next patterning step reduced the width of the microbridges to produce 14 device structures of 1.5 μm width but did not alter the 10 μm test strip. Fig. 3 shows a further reduction in T_c resulting from the second processing step, which reduced the microbridges to 1.5 μm wide bridges. Specifically, the resistance vs. temperature curves of a 10 μm wide by 25 nm thick YBCO test structure (b) and a typical 1.5 μm wide microbridge device

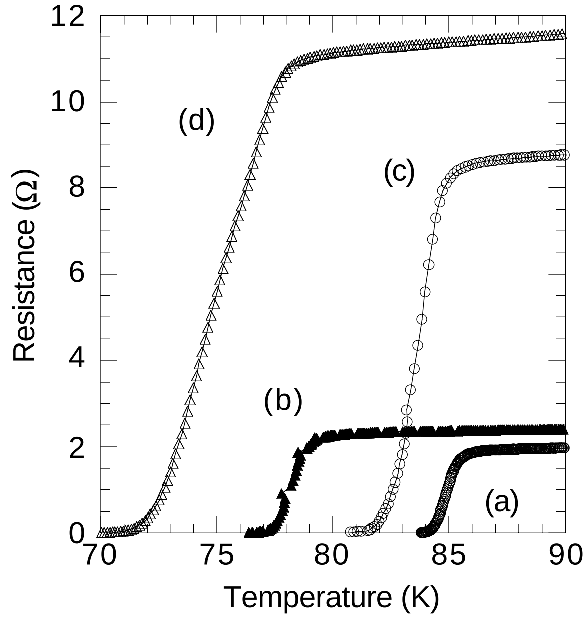

Fig. 3. Resistive transition measurements of 25 nm x 10μm YBCO test strip (b) and post second processing 1.5 μm microbridge (d); and a 45nm x 10 μm YBCO test strip (a) and post second processing 1.5 μm microbridge (c).

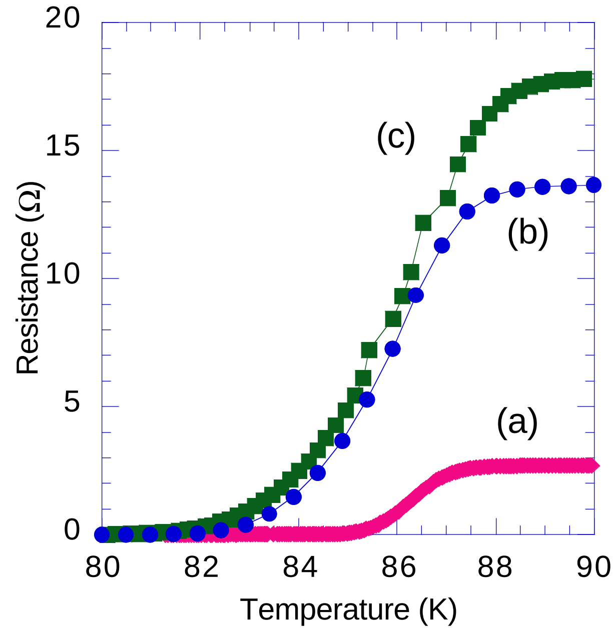

Fig. 4. Resistive transition measurements of 25 nm YBCO film on sapphire substrate before patterning(a), after 1.5 μm bridge patterning (b), and after removal of thin Au layer (c) to expose the YBCO bridge region.

(d) showed a decrease in T_c from 77 K to 71 K. Similar curves of a 10 μm wide by 45 nm thick YBCO test structure (a) and another typical 1.5 μm wide microbridge device (c) showed a decrease in T_c from 84 K to 81 K. This effect is related to damage in the YBCO films from the processing sequence and the repeated thermal cycling of the measurement sequence. In practice we can reduce the film damage by eliminating the interim-processing step and fabricating the HEB prototype microbridge structure in one processing step. Additionally, a passivation layer applied after the final processing will reduce the damage from the repeated measurement tests. There was also some observed decrease in the critical current (I_c) densities from the initial processing step through the 1.5 μm microbridge device. Typical J_c values for 1.5 μm x 25 nm thick devices measured at 4 K were 1.1×10^6 A/cm^2 and 0.4×10^6 A/cm^2 at 77 K.

A final test of device characteristics occurred after the third processing step, when the Au layer was removed from the microbridge structures. This procedure must be carefully executed with low energy ion-milling to prevent over-milling of the YBCO under-layer. Despite this care, in some cases the damage to the underlying, very thin YBCO film was so severe as to render the microbridges non-superconducting. Our experience with YBCO on Si has shown that these strained YBCO films are more sensitive to degradation from processing steps due to de-oxygenation [4]. Although they were not explicitly used in this study, it is expected that O_2 anneals will help recover the film T_c as has been observed in another study of HEB devices on $YAlO_3$ substrates [5]. A 25 nm YBCO film was grown on a sapphire substrate to test the Au-removal processing step. Fig. 4 shows the changes in the R vs. T curves of this film. The initial 10 μm test strip (a) had a T_c of 85 K, while the microbridge device structure (b) showed a T_c of 82 K. The final structure with the Au layer thinned (c) had a T_c of 81 K. The Au was nearly fully removed as determined by the resistivity of the device. The small change in the T_c demonstrates the probability of successfully removing the Au layer with this reduced energy ion-milling technique.

IV. DISCUSSION

The reduction in T_c observed after all of the processing steps can be mitigated by reducing the number of steps and by eliminating the repeated electrical testing. While great care is taken to prevent moisture contamination of the samples, every thermal cycle introduces the possibility of increased damage. The most promising result is at the critical stage of Au removal. The results seen in Fig. 4 show that there is very little additional degradation after ion milling of the Au-coated YBCO on the sapphire substrate. Similar results are expected with the YBCO on Si devices, following optimization of the YBCO film growth conditions. We have observed that certain YBCO films on Si are more susceptible to degradation, and we have conducted preliminary studies of deposition conditions varying the YBCO deposition rate and pressure, to improve YBCO film growth on Si substrates. We will also begin annealing studies, possibly with O_3, to recover superconducting properties of the microbridges.

Outstanding issues include a more accurate estimate of the effective YBCO thickness. This will be important as we begin testing sub-μm devices in existing mixer blocks, since the thermal conductance to the substrate is as yet unknown. A "dead" layer of YBCO at the interface could act as a thermal barrier, limiting the value of the device on Si. Some of our recent excellent results for films on sapphire suggest that alternative substrates may be investigated. Future work will further reduce the microbridge size to sub-micron widths through the use of e-beam lithography.

V. CONCLUSIONS

We have made microbridge devices of 1.5 μm typical size with resulting J_C of $0.1x10^6$ A/cm^2 at 77 K for YBCO film thickness of 25 nm. After Au removal the microbridges have $T_c > 70$ K. This is the first study of this kind involving YBCO devices on Si substrates intended for hot-electron bolometer applications. This study of Si-based HTS devices shows that multiple processing steps can be carried out without unacceptable damage to the prototype hot-electron bolometers.

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